



TITLE

Control Methodology for Inertial Energy Storage Devices

## BACKGROUND OF THE INVENTION

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Regulation of stored energy is essential to most machinery. Various forms of energy storage are in common usage (e.g. chemical, elastic, pneumatic). The control of power flow from inertial energy storage means has proven to be more difficult than from other forms.

Storage of energy by means of inertial energy advanced during the 1980's and 1990's through development of flywheels made from aerospace materials, rotating in near total vacuum and supported on magnetic bearings. Such devices can have energy densities equal to or greater than lead acid storage batteries.

Electrical power backup systems employing such advanced flywheels with an integral motor / generator have been commercialized. The motor function of the electrical power backup system motor / generator drives the flywheel to optimal storage speed when the normal electrical power source is available. The generator function supplies back-up electricity in the case of power outages drawing power from the flywheel.

The electrical power backup system motor / generator need not operate at a specific speed because alternating current of a specific frequency, if required, is maintained with electrical circuitry during backup power generation. The motor / generator therefore spins at a fixed ratio to instantaneous flywheel speed (not a multiple of the alternating current frequency).

Variable speed machinery that must operate at a specific speed in a specific condition (for example a vehicle) requires a control mechanism to accommodate the speed difference between the machinery and the (inherently variable speed) inertial energy storage device.

The application of a continuously variable transmission (CVT) or infinitely variable transmission (IVT) to variable speed machinery is obvious. Control of the power flow through a CVT to machinery that incorporates an inertial energy storage means has been the subject of previous patents. For example, in U.S. patent number 3672244 Mr. Nasvytis describes a "foot pedal ... connected to said [(infinitely variable)] transmission means to decrease the ratio of the transmission upon depression of the foot pedal and increase the ratio upon release of the foot pedal". The CVT is controlled directly by operator input and there is no feedback.

In cases where the CVT speed ratio is controlled directly by an operator, as with the Mr. Nasvytis' foot pedal, the CVT control position is the operator's input for speed ratio. The *rate of change* of the CVT ratio is the acceleration input. For machinery in which

the CVT ratio can change more rapidly than the machinery can accelerate, the operator must be skilled at not changing the ratio at a rate greater than the machinery can tolerate. The limitation to acceleration of the machinery will in most cases be slippage or breakage. Using an automobile for an example, the limit to acceleration is slippage of the tires; tires would slip if the speed control were changed too quickly.

In the event that the *rate of change* of the CVT ratio frequently exceeds the acceleration capability of the machinery, even momentarily, and causes slippage, energy is wasted, which is counter to the original goal of using inertial storage.

Operators of machinery need precise control of acceleration in addition to the ability to set speed. A wide variety of machinery is either powered by a combustion engine, controlled with friction braking, or both. Throttle position determines the force (torque) and therefore acceleration of the machinery. Friction braking controls force and therefore deceleration.

Due to the difficulty in controlling acceleration via rate of controller actuation, the predominance of force application controls or the energy wasted due to slippage, direct CVT control of machinery utilizing a inertial energy storage device has not been widely implemented.

An alternative to CVT control has been to utilize two motor / generators (both similar to the backup electrical power system). One motor / generator operates at the same speed as the inertial energy source, the second at the same speed as the machinery. Energy flow is regulated electrically. This system was employed in a concept vehicle developed by Rosen Motors and described in *Time Magazine*, September 23, 1996.

The cost of two motor / generator units in the two motor / generator system is a drawback of this system. Additionally, electrical motors and conductors sized to supply peak power will have relatively high electrical resistance losses at low power flows.

The prior art for control of power flow from a inertial energy source includes the utilization of a clutch or clutch systems. The clutches accommodate the speed difference between the machinery and a inertial energy storage device and regulate the power flow to and from machinery from an inertial energy storage system.

Representative of clutch systems is the teaching of Mr. Smitley in U. S. Patent 4342371. Two over-running clutches, one for forward rotation and one for reverse rotation, may be selectively engaged to transmit power to a storage flywheel through corresponding forward and reverse rotating magnetic clutches. Some slippage of the magnetic clutches is anticipated.

The drawback of clutch systems, whether frictional or magnetic, is that slippage will dissipate energy that could, in the absence of slippage, be transmitted to the machinery or stored in the flywheel.

## BRIEF SUMMARY OF THE INVENTION

The present invention is a control methodology for an inertial energy storage device that utilizes a continuously variable transmission (CVT). The CVT ratio is a function of an error signal equal to the difference between operator input and CVT output torque.

This methodology continuously synchronizes the speeds of the inertial energy storage device and powered machinery, keeping frictional losses to a minimum.

Operator input may be a positive or a negative value, a negative value corresponding to regenerative power. Operator input is force or torque analogous to throttle opening or braking effort.

## BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

The present invention is shown schematically in Figure 1. The inertial energy storage means 1 (shown as a flywheel) is coupled directly to the machinery 3 (shown as a wheel) through CVT 2. Elasticity between the CVT 2 and machinery 3 is shown in Figure 1 as spring 4.

Figure 2 is a block diagram using the Laplace variable "s" representing an embodiment of the present invention in which the CVT ratio is equal to the time integral of an error signal.

Block diagram Figure 3, also using the Laplace variable "s", represents an embodiment of the present invention in which an additional feedback loop is incorporated.

Computation may be performed with linear units or angular units.

In Figures 1, 2 and 3  $V_1$ ,  $V_2$  and  $V_3$  represent the rotational velocity of the flywheel, the CVT output and the powered machinery respectively.

In both Figure 2 and Figure 3 the notation is as follows:

$S$  = Laplace variable

$M_1$  = Mass or moment of inertia of the flywheel 1

$M_3$  = Mass or moment of inertia of the powered machinery 3

$K$  = Spring Rate (linear or rotational) of elasticity 4 between the CVT 2 and machinery 3

$F$  = Force or torque acting across elasticity 4 between the CVT 2 and machinery 3

The mass or moment of inertia of the output shaft of CVT 2 and elasticity 4 (which would be  $M_2$ ) is low compared to  $M_1$  and  $M_3$  and ignored.

The CVT is represented by a block labeled "CVT". The input to the CVT is R, the instantaneous ratio. The CVT has the following effects:

$$\text{Force or torque acting on } M_1 = F \times 1/R$$

$$V_2 = V_1 \times R$$

## DETAILED DESCRIPTION OF THE INVENTION

The present invention is a control methodology for a inertial energy storage device that utilizes a continuously variable transmission (CVT). Control of the CVT speed ratio is based on feedback of the CVT output torque. With this control methodology, the operator inputs force or torque just as with an engine or brake. The methodology employs no clutches or other slipping mechanisms and therefore dissipates only the hysteretic losses in metallic elastic structural elements, including the CVT.

The present invention is shown schematically in Figure 1. The inertial energy storage means 1 is coupled directly to the machinery 3 through CVT 2.

Advantage is taken of the inherent elasticity of the coupling shafts. If however, inherent elasticity is insufficient for control purposes, a discrete spring may also be included in the system between CVT 2 and machinery 3. This elasticity, whether inherent or discrete, is shown schematically in Figure 1 (and referred to herein) as spring 4.

Referring to Figure 1 the output speed of the CVT,  $V_2$ , is equal to the speed of the inertial energy storage means times the instantaneous CVT speed ratio,  $V_1 \times R$ . At equilibrium the average CVT output speed  $V_2$  must equal the average machinery speed  $V_3$ . At any time  $V_2$  is greater than  $V_3$  deflection of spring 4 will increase thereby increasing the force acting across spring 4 in proportion to the stiffness of spring 4. (Force decreases when  $V_2$  is less than  $V_3$  with the sign convention that negative force decelerates machinery 3.)

In the present invention the CVT speed ratio is increased or decreased as a function of either the measured deflection of spring 4, or the measured force across spring 4.

In a physical system a clutch in series with the CVT may be included to completely disengage the machinery from the inertial energy storage means when the machinery is either at rest or at a speed in excess of the capability of the CVT. However, the clutch is not considered to be a component of the power regulation control system. The clutch does not slip in normal operation, although it may be engineered to act as a force or torque limiter.

In a physical system a fixed ratio transmission in series with the CVT may be included to allow the CVT to operate in the design speed range of the CVT. A fixed ratio transmission may also provide "reverse" capability for the machinery. However, the fixed ratio transmission is not considered to be a component of the power regulation control system.

Control system dynamics are analyzed using block diagrams and the Laplace variable. This method is most useful when the control system is linear or can be linearized.

A CVT can be represented mathematically by multiplication of a ratio times an input speed. Multiplication is extremely nonlinear invalidating block diagram analysis. However, the control system block diagram can be used to illustrate the control methodology of the present invention.

Block diagram Figure 2 represents an embodiment of the present invention in which the CVT ratio is equal to the time integral of an error signal ( $1/s$  in the Laplace domain). The error signal is the difference between operator input force and the force in spring 4, labeled  $F_4$ . With initial conditions of  $V_2$  not equal to  $V_3$ , this control system will synchronize  $V_2$  with  $V_3$  after a number of oscillations. The error signal becomes zero when the spring force equals the input force, in which case the time integral (which is the CVT ratio) remains constant.

The time integral in the embodiment represented by figure 2 is *not* classic P-I Proportional – Integral feedback.

Block diagram Figure 3 represents an embodiment of the present invention in which an additional feedback loop is incorporated. In the absence of operator input or force in spring 4 CVT ratio  $R$  is  $V_3 / V_1$  such that  $V_2 = V_3$ . With operator input, spring force increases until the spring force equals the operator input, in which case the error signal is zero and once again  $V_2 = V_3$ .

In the second embodiment the error signal feedback behaves similarly to feedback elements in a linear controls systems despite the non-linear nature of the CVT. Proportional, Proportional – Integral (P-I) feedback, Classical Proportional – Integral – Derivative (P-I-D) feedback or other well understood methods may be applied to achieve desired control.